Scaling Effects of Standing Crop Residues on Aerodynamic Transfer Processes

R. M. Aiken, Kansas State University, Colby, Kansas 67701, raiken@oznet.ksu.edu

D. C. Nielsen, USDA-ARS, Akron, Colorado, dnielsen@lamar.colostate.edu

L. R. Ahuja, USDA-ARS Fort Collins, Colorado 80926, ahuja@gpsr.colostate.edu

Introduction

Standing senescent stems increase the aerodynamic roughness of the surface, reducing wind energy available for momentum transfer at the soil surface, such as for wind erosion, and also the soil-atmosphere convective exchanges of heat, water vapor, and trace gases. These roughness elements alter convective exchanges and near-surface (<0.05 m) wind velocities by absorbing kinetic energy and modifying aerodynamic roughness. These effects are readily quantified as a log-linear decrease in wind velocity relative to distance above the land surface. The slope of this relationship reflects the friction velocity, while the intercept can be interpreted as the aerodynamic roughness of the surface, or roughness length. Vertical stems tend to raise, or displace, the level of near-zero wind velocity; while increasing aerodynamic roughness and altering friction velocity (Pereira, and Shaw, 1980). Though displacement height and aerodynamic roughness are phenomenological coefficients, they tend to scale with crop canopy characteristics (height: Campbell, 1973; leaf area: Choudhury and Monteith, 1988). Analogous relationships exist between residue architecture (horizontal projected stem area) and threshold velocities required to initiate soil erosion (Hagen, 1996).

Our research objective was to derive a modified algorithm, which quantifies effects of standing stems on wind profiles above and within sparse canopies and to conduct field measurements in standing residues of wheat, corn, millet, and sunflower for wind profiles and geometries to validate the modified algorithm.

Method and Materials

Extending wind profile theory to sparse canopies of standing crop stems requires a procedure to quantify the aerodynamic parameters d and z_o. We hypothesize that in sparse canopies, these effects are proportional to silhouette area index (SAI), the horizontal projected area of roughness elements per unit of land area (Nielsen and Aiken, 1998) analogous to similar relations derived for crop canopies. Specifically, we extend the algorithm of Choudhury and Monteith (1988) to standing stems, specifying d/h, relative displacement height, as a function of aerodynamic drag (C_{fd}, dimensionless) and SAI.

$$\frac{d}{h} = 1.1 * \ln\left(1 + \left(C_{fd}\, SAI\right)^{0.25}\right) \tag{1.}$$

Following Shuttleworth and Gurney (1990), we compute z_o as the sum of roughness lengths for standing stems ($z_{o(st)}$) and surface ($z_{o(s)}$) layers, where $z_{o(st)}$ is represented, according to Choudhury

and Monteith (1988), as

$$\frac{z_{o(st)}}{h} = a \cdot \left(C_{fd} \cdot SAI\right)^{0.5} \qquad \left(C_{fd}SAI\right) < 0.2 \qquad (2.)$$

$$\frac{z_{o(st)}}{h} = a\left(1 - \frac{d}{h}\right) \qquad \left(C_{fd}SAI\right) > 0.2$$

with the value of a set to 0.3. Here the aerodynamic drag coefficient C_{fd} represents form drag of individual residue elements, perpendicular to fluid flow, distinguished from skin drag, tangential to fluid flow. We compute SAI from

$$SAI = d_s \cdot h \cdot N \qquad (3.)$$

where d_s is stem diameter (m), h is stem height (m), and N is number of stems per square meter.

We conducted field studies to determine the predictive accuracy of an algorithm derived for plant canopies to scale effects of standing crop residues on the wind profile. We used this algorithm to calculate displacement height and roughness length of standing crop residues related to the log wind profile equation. We also calculated apparent roughness length from wind profiles measured under neutral stability conditions over stems of wheat (*Triticum aestivum*), corn (*Zea mays*), millet (*Panicum miliaceum*), and sunflower (*Helianthus annuus*) using calibrated single-needle and cup anemometers at up to 10 heights ranging from 0.07m to 2.40 m above the soil surface on fields with fetch:height ratios exceeding 200:1. We compared roughness length and wind profiles computed using Eqs. 1 and 2, and measured standing stems, with those computed from field observations of wind profiles under neutral stability conditions.

Results and Discussion

Residues at the selected experimental sites were typical of those found in semi-arid cropping systems. Sunflower stubble represented the simplest system, with roughness elements approximating the shape of thin vertical cylinders. Corn stubble, comprised of husks, leaves, and broken stems, added complexity to the roughness elements. The tillering growth habit of wheat added to row orientation effects, resulting in a stiff hedge structure. The millet field was planted on ridges (height of 30 mm and spacing of 0.21 m) into standing wheat stubble.

A least-squares fit of roughness length calculated by an algorithm derived for crop canopies indicated a systematic, positive bias when it was applied to standing stems (Fig. 1). After adjusting for bias, calculated windspeeds generally were contained in 80% confidence intervals for observations above and within the crop stubble (Fig. 2). Predictive root mean square errors (RMSE) within profiles ranged from 0.5 to 4.6% of reference wind speed. The adequate fit is expected, because the revised coefficient, a, for Eq. 2 was derived from wind profiles observed above the roughness elements. The nonlinear forms of the scaling algorithms are consistent with theory and wind tunnel observations, representing an advance over schemes assuming a linear relation with residue height.

The scaling approach represented by Eqs. 1 and 2 is adequate to quantify effects of standing stems on wind speed profiles above and within these roughness elements. Further evaluation of the coefficient a used in Eq. 2 is warranted, because we used the same profile data

to derive the coefficient and to evaluate subsequent wind speeds. Further work also is required to evaluate the adequacy of Eqs. 4 and 5 for drag partitioning and to investigate aerodynamic properties of complex surfaces containing ridges and standing stems. The similarity between our results and those of Raupach (1992) and Hagen (1996) indicates that the algorithms may be suitable for process-level wind erosion and drag partitioning, though further work is warranted. Application to momentum transfer problems requires further investigation of drag partitioning.

References

Campbell, G.S. 1973. An Introduction to Environmental Biophysics. Springer-Verlag, New York. 159 pp.

Choudhury, B.J., Monteith, J.L. 1988. A four-layer model for the heat budget of homogeneous land surfaces. Q. J. R. Meteorol. Soc. 114:373-398.

Hagan, L.J. Armbrust, D.V. 1994. Plant canopy effects on wind erosion saltation. Trans. ASAE 37(2):461-465.

Nielsen, D.C. and R.M. Aiken. 1998. Wind speed above and within sunflower stalks varying in height and population. J. Soil and Water Cons. 53(4):347-352.

Pereira, A.R., Shaw, R.H. 1980. A numerical experiment on the mean wind structure inside canopies of vegetation. Agric. Meteorol. 22:303-318.

Raupach, M.R. 1992. Drag and drag partition on rough surfaces. Boundary-Layer Meteorol. 60:375-395.

Shuttleworth W.J., Gurney, R.J. 1990. The theoretical relationship between foliage temperature and canopy resistance in sparse crops. Q. J. R. Meteorol. Soc. 116:497-519.
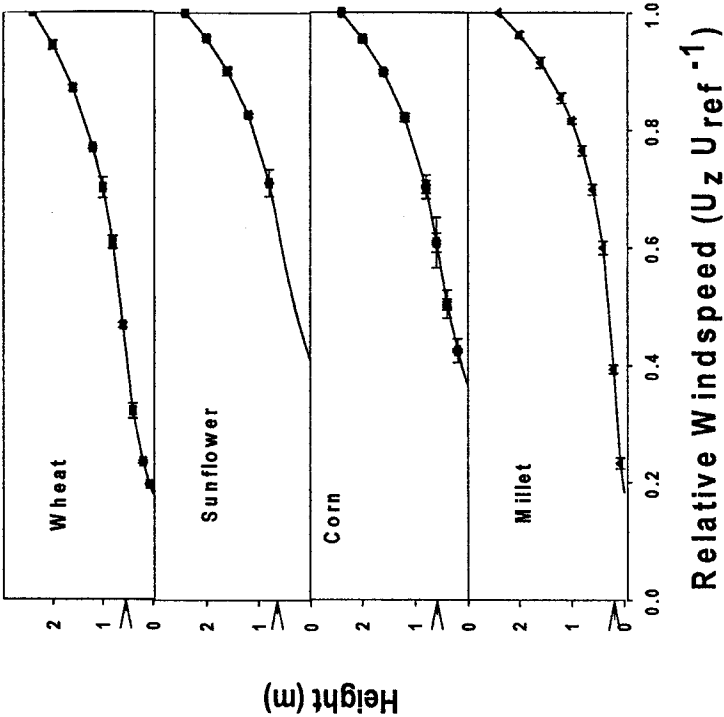
Figure 2. Relative wind speed, scaled to wind speed at reference height (2.4 m) above and within standing stems of wheat, sunflower, corn, and millet. Height is presented on the vertical axis; arrows indicate height of standing stems. The continuous function was calculated from the wind profile equation parameterized by Eqs. 1 and 2 using a fitted value of 0.24 for the coefficient '*a*'. Observed wind speeds and direction relative to row orientation are depicted with 80% confidence intervals constructed from standard errors about the means.
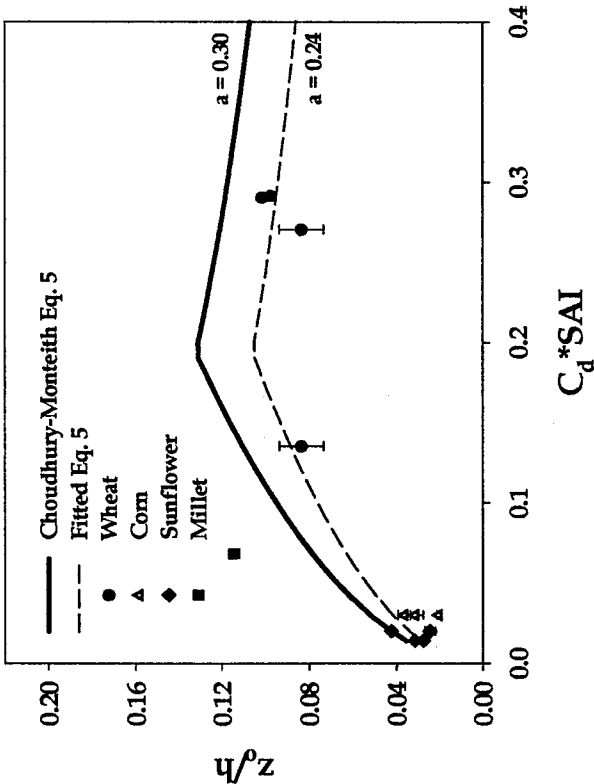

Figure 1. Roughness length, scaled by height of standing stems and depicted in relation to canopy drag. The continuous function was calculated from Eq. 2 using suggested (Choudhury and Monteith, 1988) and fitted values for the coefficient '*a*'. Observed roughness length and 80% confidence intervals constructed from standard error about the means were calculated from wind profiles over standing crop residues.